Biomass Conv. Bioref. (2011) 1:55–61
DOI 10.1007/s13399-011-0004-4

REVIEW ARTICLE

Hydrogen from biomass: large-scale hydrogen production based on a dual fluidized bed steam gasification system

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Received: 20 September 2010 / Revised: 17 January 2011 / Accepted: 20 January 2011 / Published online: 8 February 2011

Abstract Hydrogen is used as an important feedstock for the chemical industry. Common production technologies for the production of hydrogen from fossil fuels today cause relevant CO_2 emissions. Hydrogen from renewable energy sources is discussed as an alternative option to replace traditional feedstock and can therefore be part of a low-carbon energy system. This paper describes the results of a simulation of a concept for the production of hydrogen with biomass as feedstock. The described investigations include a possible process design, the process simulation using the software IPSEpro, a description of the operation characteristics, and a profitability analysis of the applied hydrogen production concept. The simulation result shows that 61 MW of hydrogen can be produced from 100 MW wood chips and 6 MW of electricity. As a result, hydrogen production costs of 54 €/MWh can be estimated. For the investigated concept, the wood chip price is the most important factor for the hydrogen production cost followed by investment costs for the plant and the realized plant operation time per year.

Keywords Biomass · Gasification · Hydrogen · Membrane · Plant simulation

1 Introduction

The world's energy system today is facing increasing challenges regarding its environmental, economical, and social sustainability. Continuation of our current way of energy consumption would lead to a catastrophic and irreversible damage to the global climate by increasing the global mean temperature by 6°C in 2100 compared to 1850. Such an increase would imply major economical and social crises all over the world. To avoid such a scenario in the future, a rapid transformation to a low-carbon, efficient, and environmentally benign system of energy supply is required [1].

For the realization of a low-carbon energy system, the development of new energy carriers is needed because most energy carriers today are based upon fossil energy sources. For this reason, hydrogen produced from renewable energy sources is discussed as an alternative to fossil energy carriers. Hydrogen can be used as an energy carrier, for energy storage applications, as fuel for fuel cells and as fuel for combustion engines. Furthermore, hydrogen is used as an important feedstock for the chemical industry. Common production technologies for the production of hydrogen today cause relevant CO_2 emissions. The combustion process of hydrogen itself is free of CO_2 emission and can therefore be a part of a low-carbon energy system. It is important to note that there is still some research required to meet the challenges regarding the storage of hydrogen and the production from renewable energy sources [2].

For the production of hydrogen so far, mainly natural gas and naphtha are used as feedstock. The most common production technology is the steam reforming of natural gas. But also production technologies like partial oxidation or autothermal reforming of fossil fuels are used for industrial applications [3, 4]. All of the so-far mentioned production technologies have in common that they cause relevant CO_2 emissions. To meet the goal of a "low-carbon energy system," hydrogen can only be an option if it is produced from renewable energy sources. The production

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of hydrogen by applying the electrolysis of water can at this point only be considered as an opportunity if the used electricity is supplied by renewable resources like wind or sunlight. Promising ways for the production of hydrogen are biomass-based production technologies. These production technologies are still under development, and only few data about plants and their operation are available up to now. Therefore, it is difficult for energy policy decision makers to identify the advantages and disadvantages of production technologies based on biomass feedstock [5].

In this area, more research is necessary to be able to quantify the disadvantages and advantages of hydrogen production from biomass. Can hydrogen from biomass be produced at affordable costs? Which improvements of the production technology would be necessary to reach affordable costs? Which production method can achieve the best efficiency and the highest hydrogen output? Previous studies have shown that alkaline electrolysis shows high energy efficiency among the renewable production technologies. But also the reforming of biomass gasification gas shows good production efficiencies [5].

Gasification of biomass is the thermochemical conversion of solid biomass to combustible gases with significant hydrogen content. Therefore, gasification is an appropriate process step for the production of hydrogen from solid biomass [6]. The following research results should help to answer the mentioned questions around hydrogen production from biomass and quantify the characteristics of a hydrogen production plant from biomass basing on a dual fluidized bed steam gasification system and a gas permeation membrane. The following chapters include:

- the process simulation,
- the process design,
- the operation characteristics, and
- a profitability analysis

of a hydrogen production plant concept.

2 Concept and methodology

The following investigations describe the evaluation of a hydrogen production concept with 100 MW biomass as feedstock. The results of the investigations should quantify the advantages and disadvantages of the analyzed production concept. A useful tool for the evaluation of a power plant concept is process simulation. For the calculation of the hydrogen plant parameters, the simulation software IPSEpro has been used. IPSEpro has been part of several successful development processes at the Vienna University of Technology and has proven its reliability in many process design simulations in the past. IPSEpro enables an efficient and quick calculation of mass and energy balances for a modeled process design. The applied process design for the production of hydrogen is basing on the experiences made with biomass gasification in Güssing, Austria. In Güssing, the gasification of biomass with a dual fluidized bed has been successful demonstrated.

The process design plays a crucial role for the performance of a plant configuration. Figure 1 illustrates a general overview over the chosen process design for the simulation of the hydrogen production plant. The starting point of the hydrogen production is the gasification of biomass in a dual fluidized bed steam gasification system. Two separate gas streams are the product of the gasification system. The product gas stream contains the chemical energy of the gasified wood chips. After further gas treatment steps, the product gas contains a high amount of hydrogen which can be separated from the main product gas stream. The evaluated process design contains a dual fluidized bed steam gasification system with olivine as bed material. This gasification system has been chosen because it offers the possibility to produce a product gas with high energy density and high hydrogen content and this technology has already been successfully demonstrated on a larger scale. A promising way for a further future development of the evaluated process design would be the implementation of a dual fluidized bed steam gasification system using lime as bed material to selectively transport CO_2. This would lead to a higher hydrogen content of the product gas at the exit of the gasification system and reduce therefore the necessary gas treatment [7].

The flue gas stream is the result of a separate combustion process which delivers the necessary heat for the gasification and can be used for the recovery of process heat. Figure 2 illustrates the applied process design more in detail. The treatment of the product gas stream should ensure a high share of hydrogen. In a first step, the gas stream gets reformed in a steam reformer at a temperature between 750°C and 850°C. In a second step, the product gas gets converted in a CO-shift reactor at a temperature of 350°C. Table 1 shows the development of the product gas stream at the different stages.

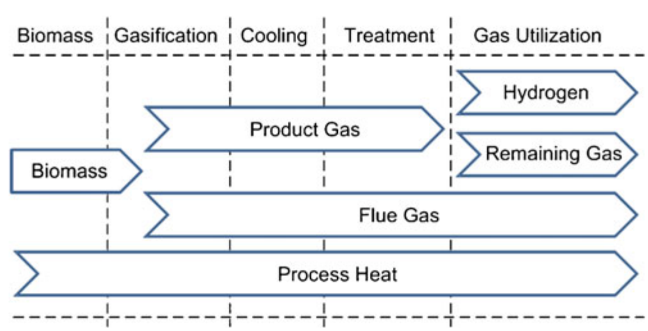

Fig. 1 Process design

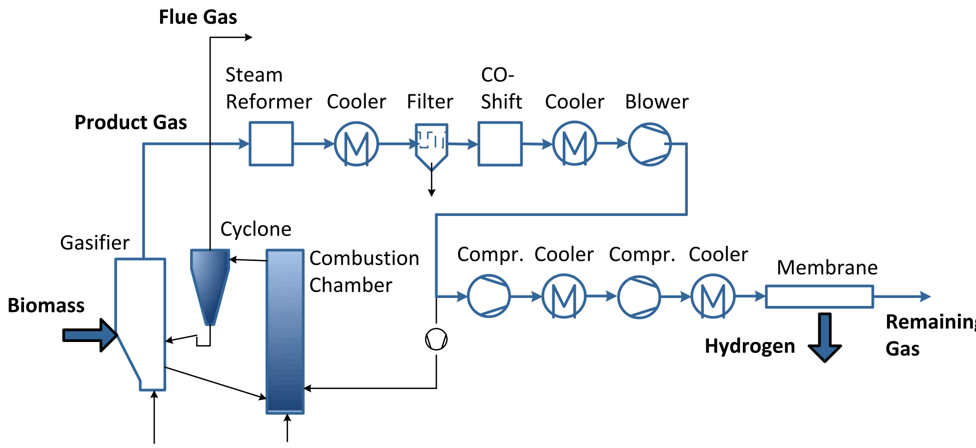

Fig. 2 Detailed process design

After the CO-shift reactor, the product gas stream contains a high amount of hydrogen. The hydrogen needs to be separated from the other fractions in the product gas stream. For the separation of hydrogen from the remaining gas, the application of a hydrogen purification technology is necessary. There are different purification systems available:

- Cryogenic separation
- Pressure swing adsorption (PSA)
- Membrane separation

The different hydrogen purification systems are basing on different separation principles. So, the process characteristics differ significantly. The selection of the appropriate separation method depends not only on the economics but also on process flexibility, reliability, and the way of the hydrogen utilization [8].

In the investigated case, a polyamide gas permeation membrane has been implemented in the process design. The behavior of the membrane is currently under experimental investigation together with a scientific cooperation partner, and the simulation results of the plant concept should give feedback about the characteristics of the implementation of such a membrane in a 100-MW plant configuration. The low pressure of the hydrogen product is a disadvantage of the separation with membranes because for most hydrogen utilization cases, the hydrogen is needed at high pressure. To reach this pressure, another compression is necessary which leads to higher electricity consumption. An alternative method for the separation of hydrogen from the product gas would be by applying PSA processes. PSA systems offer high separation efficiencies and design flexibility [9]. PSA systems are common for the industrial production of hydrogen from natural gas and in small-scale configurations like oxygen production from air and biogas separation. On the other hand, the complexity of PSA systems can be a disadvantage for the application in small- and medium-scale plant configurations. The decision between a membrane and a PSA system depends on the utilization of the hydrogen. If high purity of the hydrogen is needed, PSA devices deliver better results regarding purity and energy efficiency. The membrane has been chosen for the hydrogen separation process because it is a simple system and well established in the production of hydrogen from natural gas and in different fermentation gas separation processes [10].

The applied process design should ensure high efficiency with high hydrogen output and low biomass and electricity consumption. This way, low hydrogen production cost should be achieved. The process simulation software IPSEpro should quantify the advantages and disadvantages of the designed hydrogen production concept. Therefore, the detailed process design for the production of hydrogen has been modeled in an IPSEpro Project.

Table 1 Product gas composition

Product gas after…	Gasifier (%)	Steam reformer (%)	CO-shift reactor (%)	Membrane separation (hydrogen) (%)
H_2 (wf)	40.9	55.0	62.9	87.0
CO (wf)	25.0	30.0	7.3	0.2
CO_2 (wf)	19.6	12.5	27.8	12.8
CH_4 (wf)	9.9	1.4	1.1	0.01
Other (wf)	4.6	1.1	0.9	0.19

wf water free

3 Results and discussion

Figure 3 gives an impression of the IPSEpro model for the simulation of the described hydrogen production concept with 100 MW of biomass as feedstock. The calculation of the model with IPSEpro delivers the results for mass and energy balances of the modeled process design. These results demonstrate the possible hydrogen output for the modeled concept. The results show that 61 MW hydrogen (basis lower heating value) can be made from 100 MW biomass (basis lower heating value). Additionally, there is

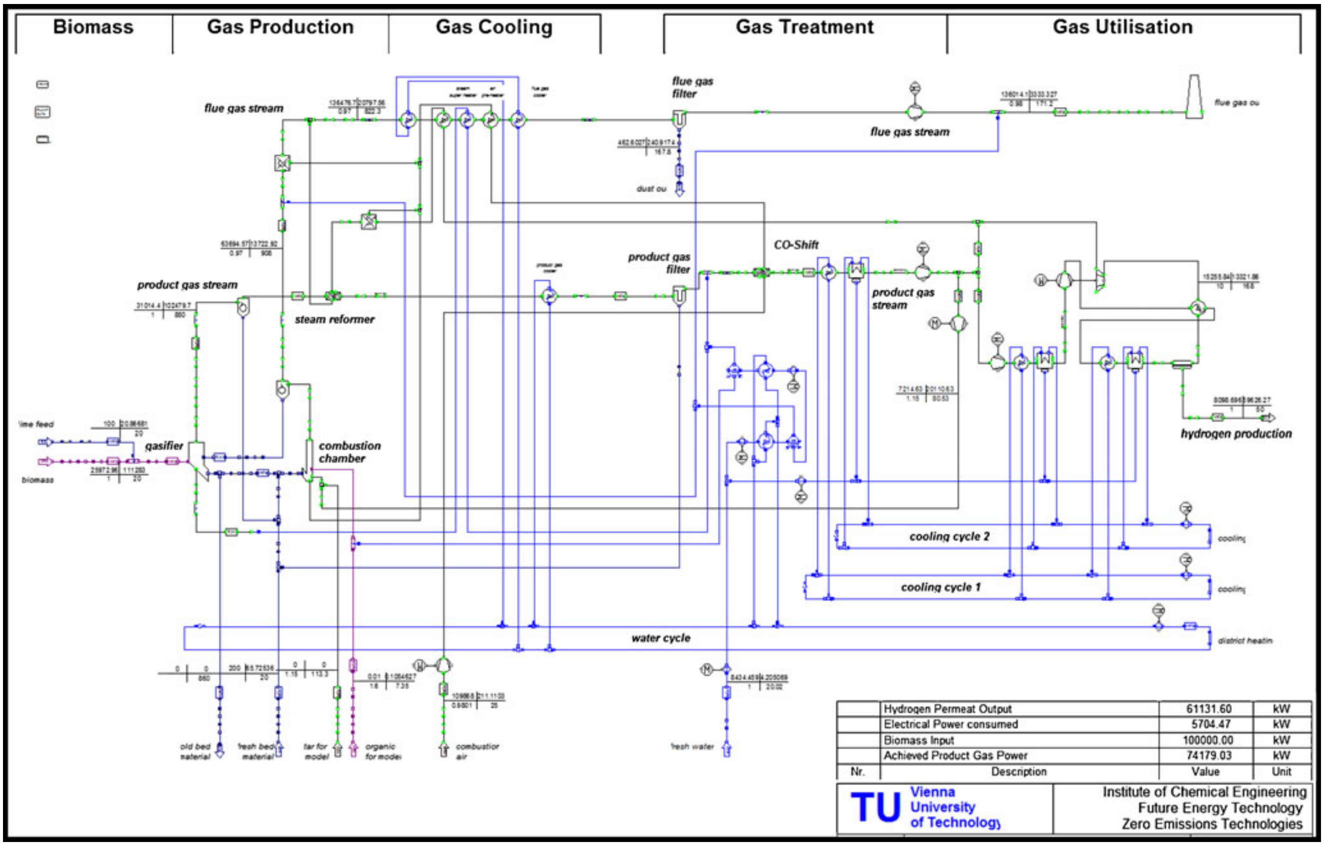

Fig. 3 IPSEpro project—concept for the hydrogen production from 100 MW biomass

6 MW of electricity necessary for the production process. As well as hydrogen process heat is also generated. This process heat could be used, for example, for district heating if there is local demand beside the plant. The results also show that 17.5 MW of heat could be used for district heating with a feed temperature of 142°C (10 bar) and a return flow temperature of 100°C (8 bar). Tables 2 and 3 show the final results of the mass and energy balances for the modeled hydrogen plant. The feed for this plant is wood chips with a water content of 20 wt.%. The wood chips get gasified in a dual fluidized steam gasification system.

After the gasification process, the produced product gas exits the gasifier with a temperature of 850°C. The produced product gas gets cleaned, cooled, and reformed as shown in Fig. 2 and Table 1. For the hydrogen separation from the remaining gas, the gas gets compressed to a pressure of 10 bar. For this compression, 3.5 MW of electricity is used and electricity is therefore a main production factor which needs to be considered. Table 2 illustrates the electricity consumption of the plant which includes the remaining pumps and blowers. The remaining gas of the hydrogen separation process is used for the generation of process heat for the gas reforming process. The gas reforming process can be heated only by the combustion of the remaining gas independently. In the case of power fluctuation, the performance of the

Table 2 Plant input

Plant input		
Biomass (wood chips)	kg/h	25 972
Biomass—water content	wt.%	20
Biomass—lower heating value	MJ/kg	13.86
Biomass—chemical energy	kW	100 000
Electricity—consumption	kW	5 714
Water	kg/h	8 434
Air	Nm³/h	85 752

Table 3 Plant output

Plant output		
Hydrogen	Nm³/h	23 782
Hydrogen—production costs	€/MWh	54
Hydrogen—lower heating value	MJ/kg	27.17
Hydrogen—chemical energy	kW	61 131
District heating	kW	17 666
Ash	kg/h	462
Flue gas	Nm³/h	102 689

steam reformer can be adjusted by additional combustion of product gas.

With the simulation of the described hydrogen production plant, the mass and energy balance of the concept have been quantified. A further perspective for the evaluation of the achieved results arises by looking at the possible profitability of the plant concept. Tables 2 and 4 show the values of the main parameters which have been considered for the cost analysis. The most important factors for the production cost of hydrogen are the wood chip price, the investment costs for the plant, and the realized operation time per year. A calculation with the illustrated values in Table 4 shows that the hydrogen production cost are 54 €/MWh.

The represented values in Table 4 refer to a simple cost calculation model for the calculation of the hydrogen production costs. The calculation results refer to the hydrogen purity shown in Table 1 at atmospheric pressure. A higher purity of the produced hydrogen and the compression of the hydrogen for transport and storage would lead to higher investment and operational costs. An evaluation of different hydrogen production plants using the methodology of a net present value calculation would need to consider alternative options with similar plant output conditions. The main purpose of this cost calculation is not to estimate the production costs exactly. The purpose is to find out about the main factors which have the most impact on the overall production cost. These factors are the critical success factors for the evaluated plant concept, and they enable a significant optimization of the process design. At this point, values for costs and prices always involve insecurity about their future development of the different cost parameters. For the evaluated plant concept, the main factors for the hydrogen production costs are the wood chip price, the investment costs, and the operational hours per year of the plant. A change of these main factors is shown in Fig. 4. This figure illustrates a possible change of investment costs, operation time, and wood chip price and their impact on the hydrogen production costs. Other cost factors like electricity consumption, nitrogen, olivine, etc., have also been included in the calculation of hydrogen production costs, but their impact is less compared to the mentioned main cost factors. The most likely expected price change would be a change of the wood chip price.

Table 4 Cost analysis

Cost analysis		
Operating hours	h/a	7 000
Wood chip costs	€/MWh	20
Electricity costs	€/MWh	90
Nitrogen costs	€/Nm³	0.06
Olivine costs	€/t	150
Lime costs	€/t	15
Labor costs	€/a pers.	45 000
Plant investment costs	€	50 000 000
Maintenance costs	%/a	0.5
Operating time	a	10
H_2 production costs	€/MWh	54

The circle in Fig. 4 marks the estimated case with a “wood chip price” of 20 €/MWh [11], 50 000 000 € “investment cost” for the plant, and an estimated “operation time per year” of 7 000 h. A change of the wood chip price has the biggest impact on the production cost of the applied production concept. Thus, the relation between wood chip price and the price of an alternative feedstock like natural gas is a critical success factor for hydrogen production concepts. This underlines the impact of energy policy decision makers by taxing and subsidizing different feedstock. Investment cost and the plant operation hours also have a major impact on the production costs.

To cover the impact of economic modeling uncertainties, different price scenarios have been calculated and illustrated in Fig. 4. Further realization steps for the evaluated hydrogen production plant need to include adequate economic methodology for the precise prediction of the costs and earnings for the first years of plant operation. The biggest uncertainties for this calculation would be the exact prediction of realized investment cost for the plant and the realized wood chip purchase price in the future. To achieve low hydrogen production cost, the plant operator needs an excellent management of the planning, construction, and operation phase of the hydrogen production plant. This would also ensure a high availability of the plant in the first years of operation. To address technical modeling uncertainties, it is important to validate the implemented model units. The implemented models have been validated in the past with experimental data from the 8–10 MW plants in Güssing and Oberwart. Especially the long time behavior of units in the process design, which have not been part of the demonstrated plants before, and their reaction on the long time application in a gasifier product gas stream need to be considered before further realization steps of the plant concept. Therefore, the data regarding the behavior of the “membrane system” and the “CO-shift reactor” need to be approved by experiment at relevant operating conditions.

The evaluated hydrogen production plant is based on a dual fluidized bed steam gasification system. This system is an indirect gasification system which has been successfully demonstrated on a large scale in Güssing and in Oberwart. A dual fluidized bed steam gasification system produces a nitrogen-free product gas with high hydrogen content and can be compactly build without the need of an air separation unit. Disadvantages compared to direct gasification systems are that the plant has to operate two separate

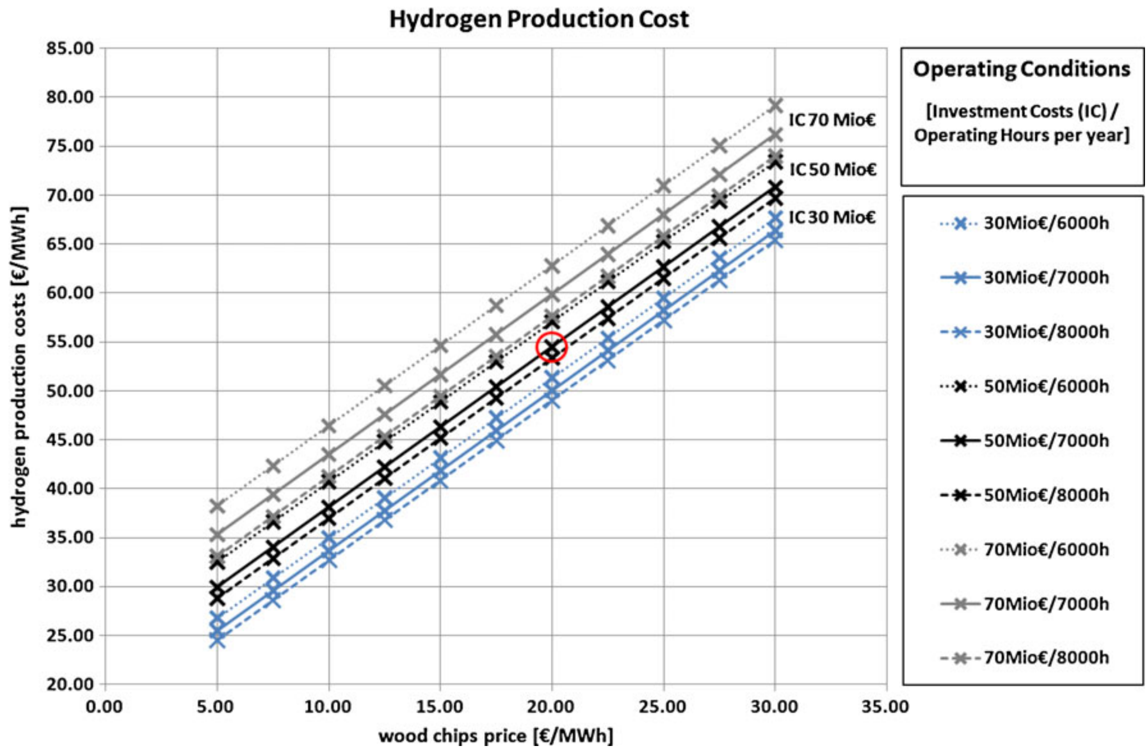

Fig. 4 Hydrogen production costs

gas streams and that it is so far demonstrated on a larger scale just at atmospheric pressure. The dual fluidized bed steam gasification technology offers good properties for the integration into a hydrogen production concept. For the further development of the hydrogen production concept, gasification using lime as bed material to selectively transport CO_2 could be an interesting option because of the higher hydrogen content of the produced product gas. The higher hydrogen content and improved product gas quality would reduce the necessary amount of gas treatment and gas cleaning. A dual fluidized bed steam gasification system using lime as bed material to selectively transport CO_2 has so far not been demonstrated on a larger scale. Also, pressurized gasification is an interesting option which could reduce the electricity consumption of the plant. Further research and development is necessary to gain the benefits of the mentioned principles.

4 Conclusion and outlook

Continuing our current way of energy consumption would lead to a catastrophic damage to the global climate. Hydrogen from renewable energy sources is discussed as an alternative option to replace traditional energy carriers and can therefore be part of a low-carbon energy system. For the production of hydrogen so far, in most cases, fossil fuels are used as feedstock. This paper describes the results of the simulation of a concept for the production of hydrogen with biomass as feedstock. The investigated concept is basing on a dual fluidized bed steam gasification system and a gas permeation membrane.

The results of the simulation with the process simulation software IPSEpro show that 61 MW of hydrogen can be produced from 100 MW wood chips. Additionally, there is 6 MW of electricity necessary for this hydrogen production concept. Furthermore, all mass and energy balances have been quantified for the modeled hydrogen production plant. The applied process design plays a major role for the performance of the plant.

In the case investigated, the process design was based on a dual fluidized bed steam gasification system, a steam reformer, a "CO-shift" reactor, and a gas permeation membrane. In this process design, the following weaknesses have been identified and need be considered before further project development. The hydrogen separation with a gas permeation membrane leads to a certain electricity consumption because of the necessary product gas compression. After the separation process, the hydrogen is delivered at a low pressure and the purity of the hydrogen product is relatively low for further utilization. Depending on the hydrogen utilization, PSA units could also deliver good overall results. At this point, further investigations are necessary to identify the advantages of the different

separation processes and their overall plant operation behavior regarding performance and harmful substances for the different process steps.

Additional to the simulation of mass and energy balances, a profitability analysis of the modeled hydrogen production plant has been carried out. This analysis shows that the wood chip price is the most important factor for the hydrogen production cost followed by investment costs for the plant and realized plant operation time per year. The hydrogen production costs are expected with 54 €/MWh of hydrogen. Because of the insecurity about future costs and price development, additional scenarios have also been quantified. The additional scenarios also underline the big impact of the wood chip price on the production costs. If hydrogen can be produced from biomass at affordable costs, it strongly depends on the relation between biomass price and the price of traditional feedstock. Therefore, energy policy decision makers play a major role by taxing and subsidizing different feedstock. To achieve low hydrogen production costs, the plant operator needs an excellent management of the planning, construction, and operation phases.

Acknowledgments We would like to thank Professor Michael Harasek and Aleksander Makaruk from the Vienna University of Technology for their support and their contribution.

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